Light Mass WIMP Searches with a Neutrino Experiment:
The MiniBooNE Search

IF5 Argonne Workshop

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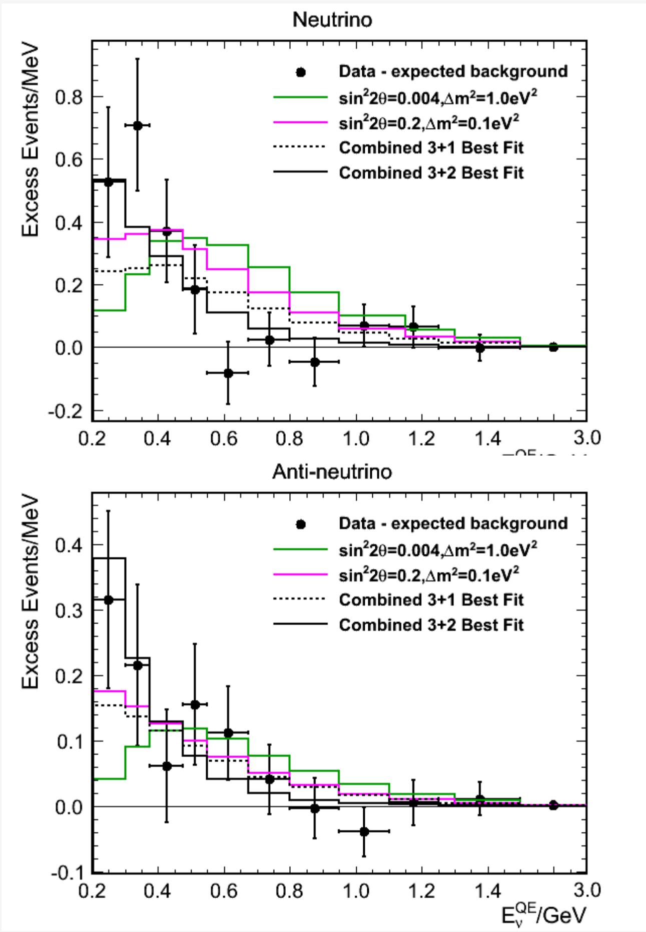
Outline

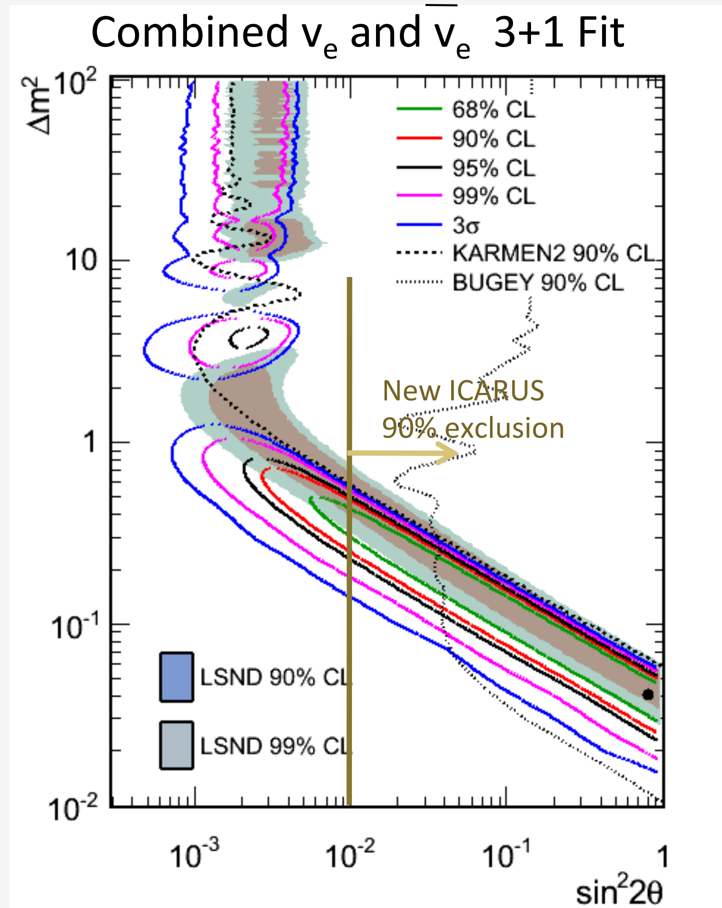
- Summary of 10 years of MiniBooNE neutrino/antineutrino running.
- The case for light mass WIMPs (<1 GeV) and how to produce them with protons beams.
  - neutrino experiments are good places to search for exotic particles.
- MiniBooNE WIMP detection methods, sensitivities and limits.
  - the case for Beam off target running.
- Future possibilities with MiniBooNE/MircoBooNE, new experiments with the Main Injector.
- Conclusions.

Ten Years of Successful MiniBooNE Running and Results!

- Neutrino mode: 6.5E20 POT
- Antineutrino mode: 11.3E20 POT
- 10 oscillation papers
- 12 cross section and flux papers
- 1 detector and 1 supernova search paper
- 17 PhD thesis
- The experiment is well understood!

Ten Years of MiniBooNE Running: Oscillation Results





- **Combined ν_e and $\bar{\nu}_e$ Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)**
- We fit for oscillations (3+1 – two neutrino model), and find consistency with LSND.
- However, with one detector, this is not proof of oscillations! Could the e or γ excess, or some part of it, be caused by a new background or other physics? **–need systematic checks**

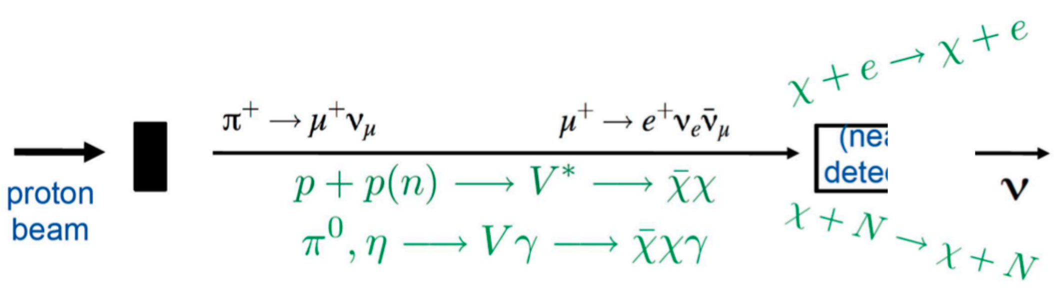
A New Idea: WIMP/Dark Sector Searches at MiniBooNE

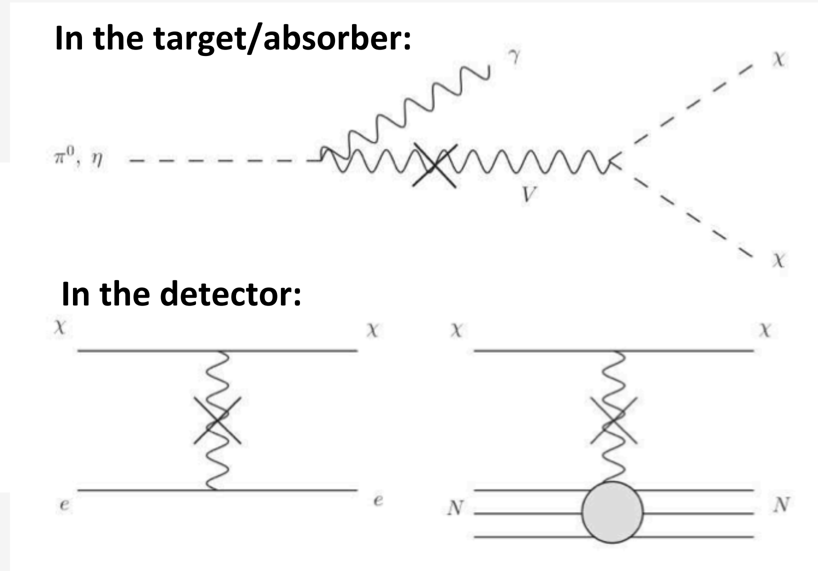
- Can WIMP Dark Matter be light (sub-GeV)?
- Yes! What are the constraints on such a scenario? What does a model look like?
- Consequences of the model for other observations, e.g. muon g-2.
- If WIMPs are light, how can MiniBooNE produce and detect them.
  – See Brian Batell's previous talk for theoretical setup.

Why are neutrino experiments (MiniBooNE) useful for new particle searches?

- Need a lots of protons on target: MiniBooNE has a total of ~$2E10^{21}$ @ E_{proton}= 8GeV.
- Detector needs to be close to source (for rate), but far enough away too minimize beam related backgrounds. MB is 500m from target.
- Massive detector (MB ~1 Kton oil).
- Good particle identification (MB reconstructs p, n, μ, e, γ).
- Good event reconstruction (for MB E_t > 20 MeV and absolute timing ~nsec).

Producing a Dark Matter Beam





Electron Elastic scattering

Nucleon Elastic scattering

- Monte Carlo Simulation of WIMP Production at MiniBooNE:
  - Use HARP-MiniBooNE Be target Sanford-Wang meson production model.
  - π^0 and η production errors range from 25% to 100%. More work to reduce these.
- Electrons and nucleon can be reconstructed in MiniBooNE with ~35% efficiency and ~10% energy resolution.
  - Nucleon systematic errors ~20% (cross section paper).
  - Electrons systematic errors ~12%, can make use of WIMP-electron forward scattering kinematics cosθ > 0.99 to reduce backgrounds by a factor of 100.

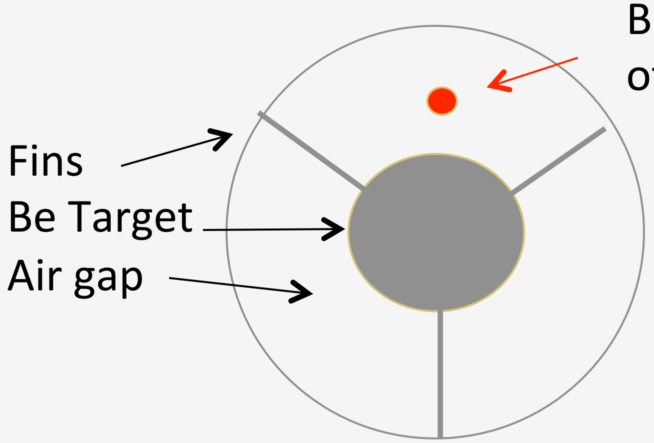
Enhancing the WIMP Search at MiniBooNE

- The WIMP scattering signal looks like neutrino nucleon or neutrino electron elastic scattering. Thus, neutrino interactions are the biggest background to these searches.
- We can employ a beam dump type method to significantly reduce charged meson decay, and hence the neutrino flux.

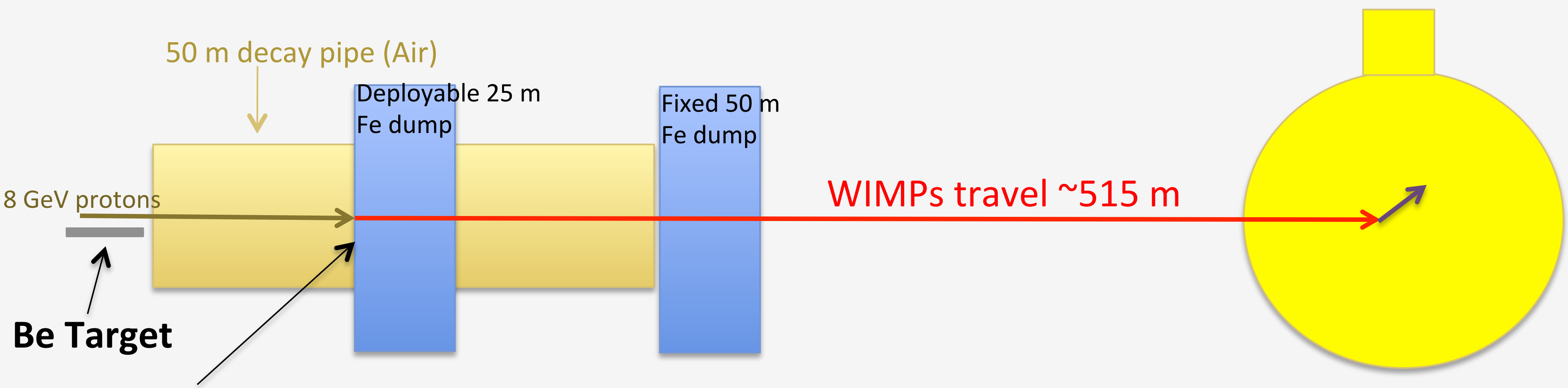
Beam Off Target Running

MB has the capability to steer the protons past the target and onto the 25m or 50m iron dump

Beam spot position in beam off target mode (~1 mm spread)



-Target is 1 cm diameter
-Air gap between target and horn inner conductor is ~1 cm

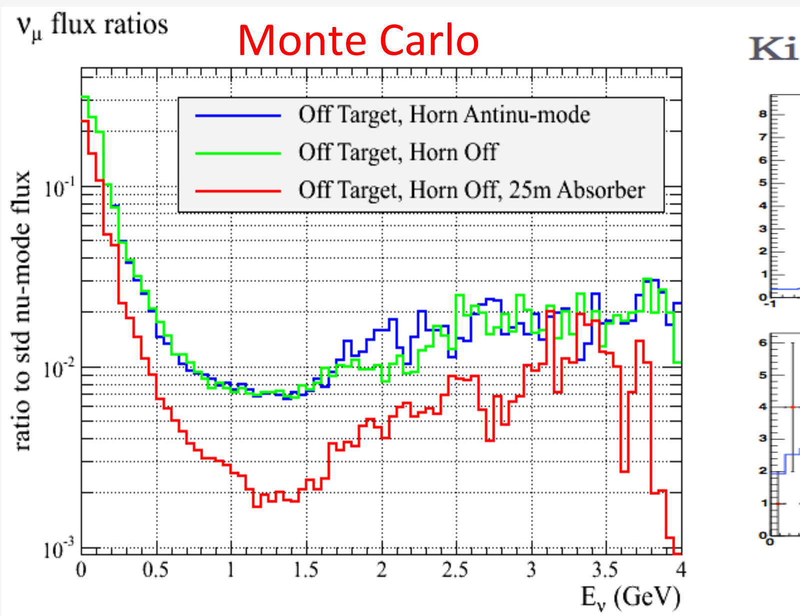


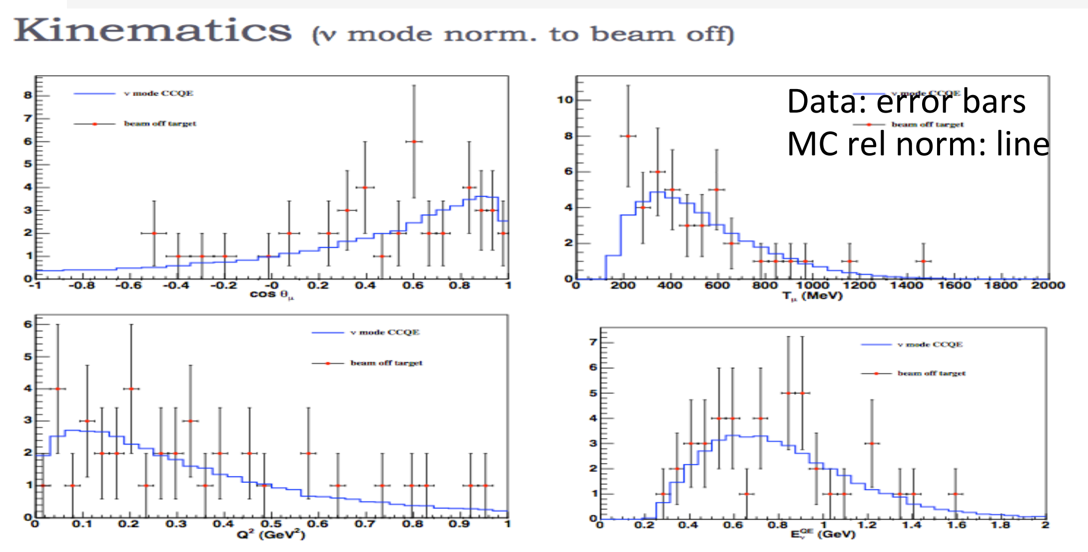
- π^0 and η produced by protons in the iron quickly decay producing WIMPs (χ)
- Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions). **Neutrino Flux reduction measured to be ~42 with 50m dump.**

Neutrino Rate Reduction with Beam Off Target Running (1 week test run)

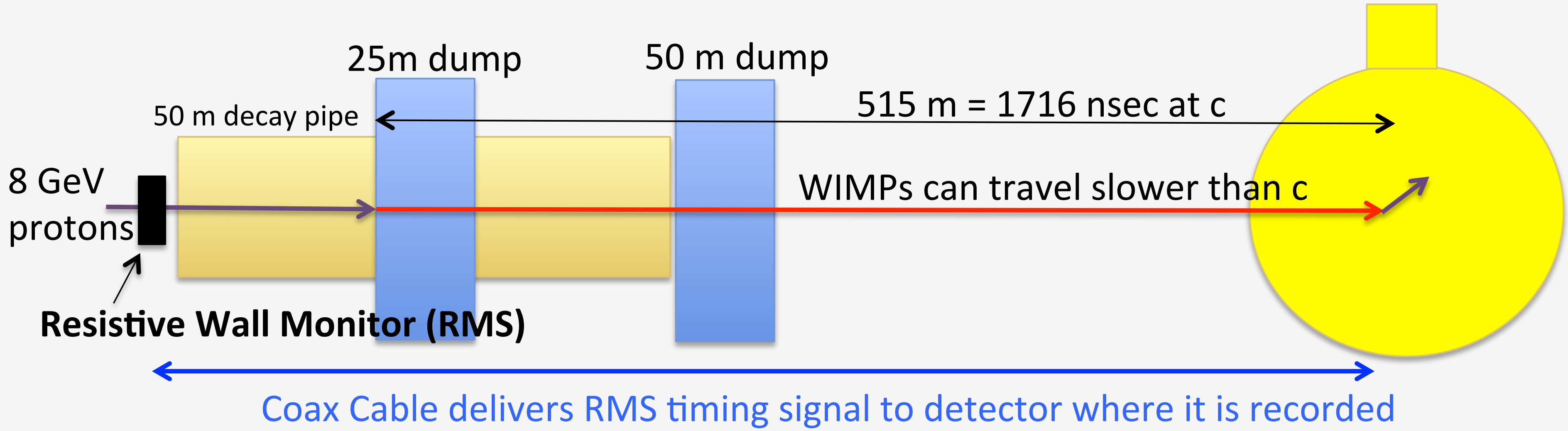
- Estimated neutrino rate reduction:
  - 50m absorber one week beam off target run (~5.54e18 POT): $(\text{events/POT})^{\nu\text{ mode}}/(\text{events/POT})^{\text{beam off target}} = 42 \pm 7$ ← Data rate reduction
  - 50m MC: $(\text{events/POT})^{\nu\text{ mode}}/(\text{events/POT})^{\text{beam off target}} = 36$
  - 25m MC: $(\text{events/POT})^{\nu\text{ mode}}/(\text{events/POT})^{\text{beam off target}} = 72$

MC flux reduction

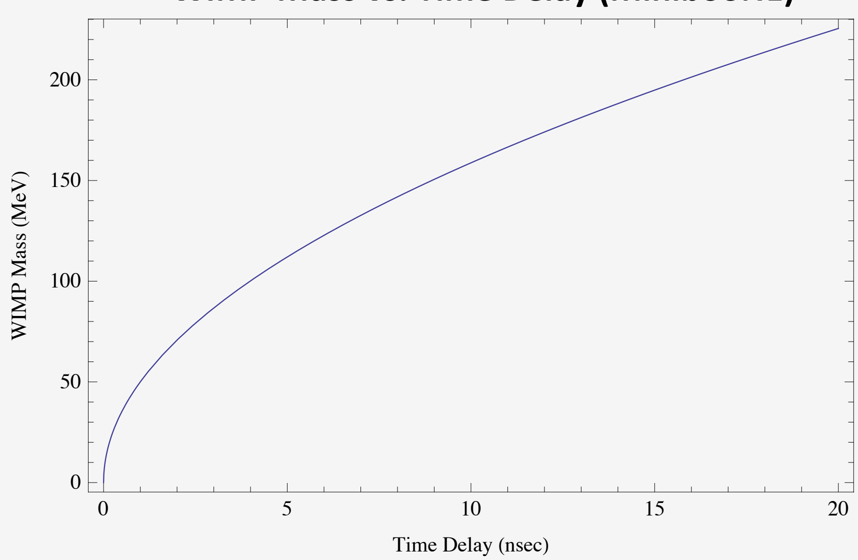




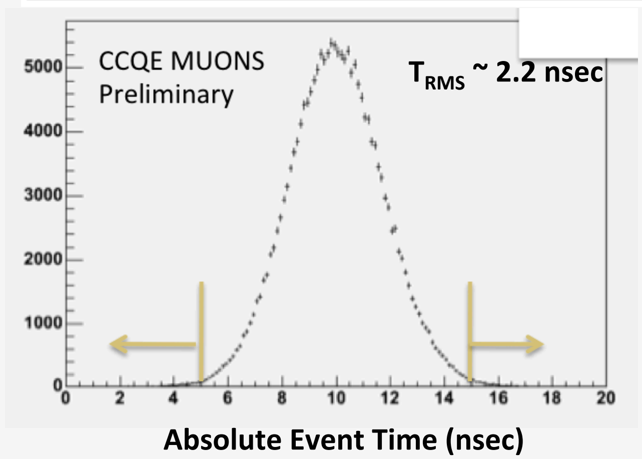
WIMP Time of Flight



WIMP Mass vs. Time Delay (MiniboonE)



Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122



-Electrons timing will be similar to muons, while NC nucleon events twice as worse.

MiniBooNE Collaboration and Theory Group Proposes Beam Off Target Run to FNAL PAC (Nov 2012)

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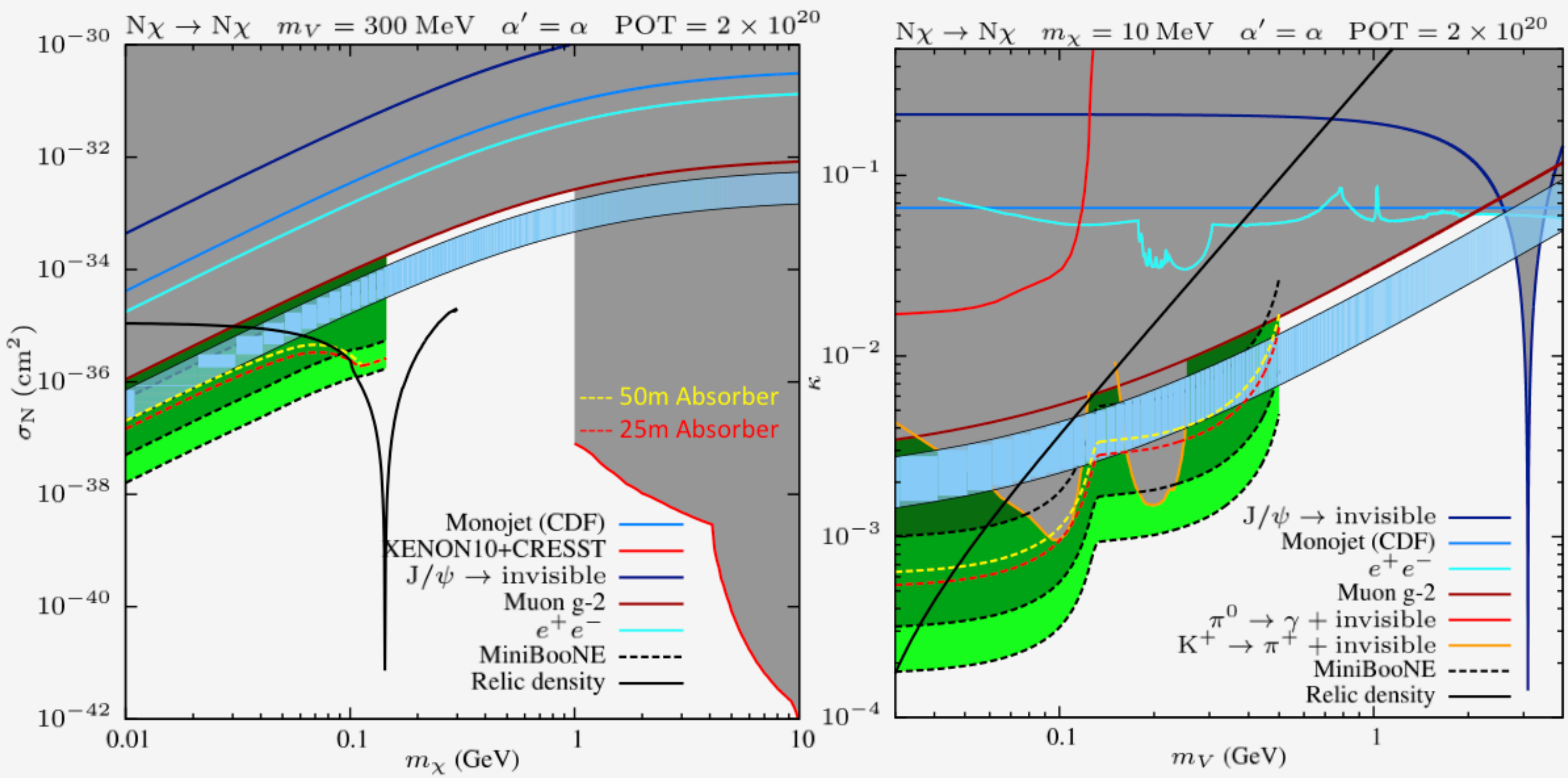
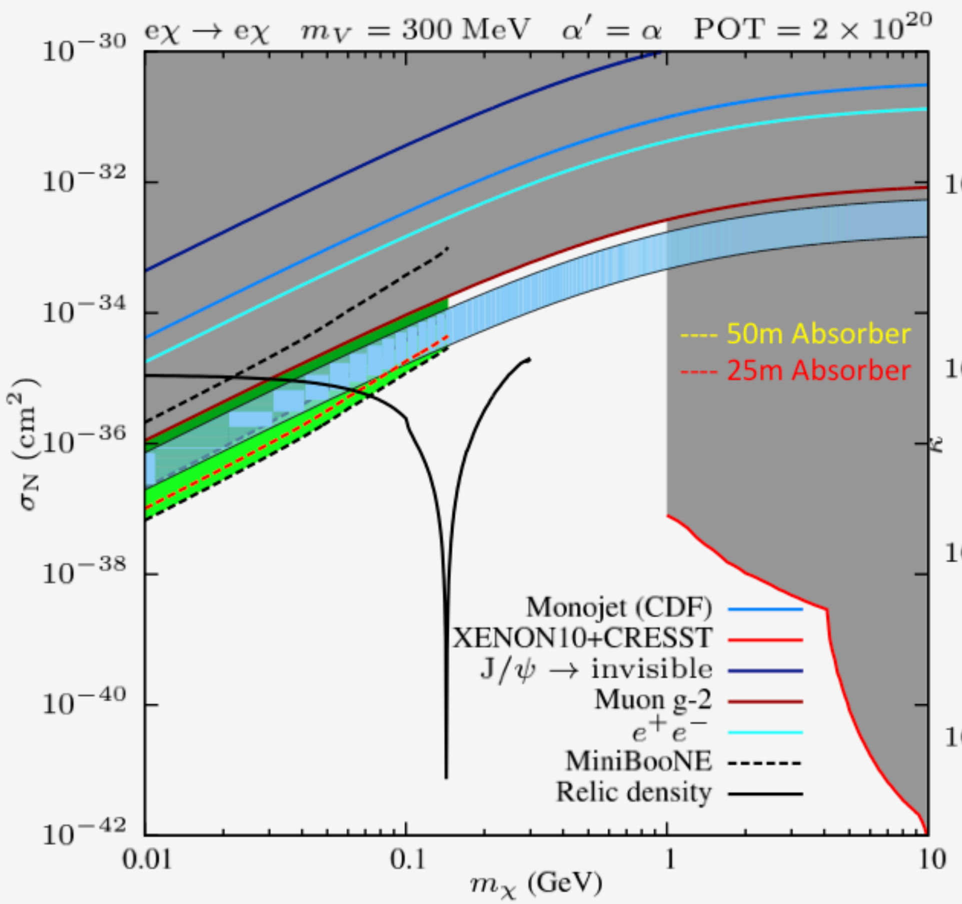
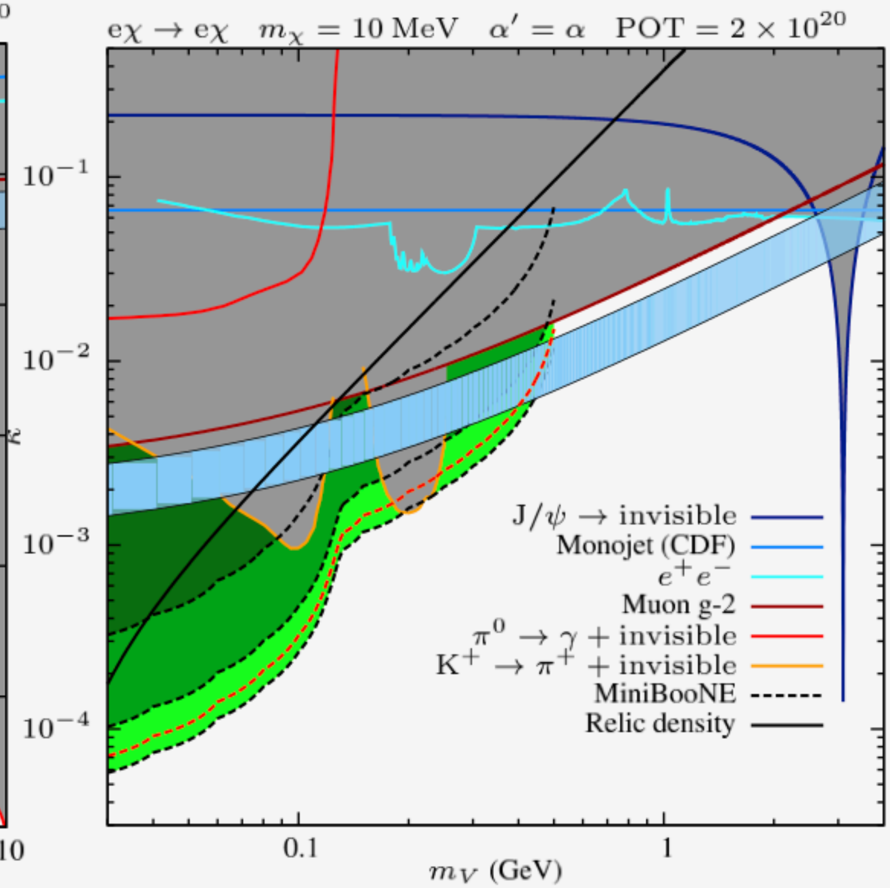
90% C.L. Sensitivities for WIMP-Nucleon Scattering: 2E20 POT Beam off Target and 25/50m Absorber Run



- Estimate 90% C.L. upper limits includes timing information.
- Can cover a significant part of the muon g-2 signal region.

90% C.L. Sensitivities for WIMP-Electron Scattering: 2E20 POT Beam off Target and 25/50m Absorber Run





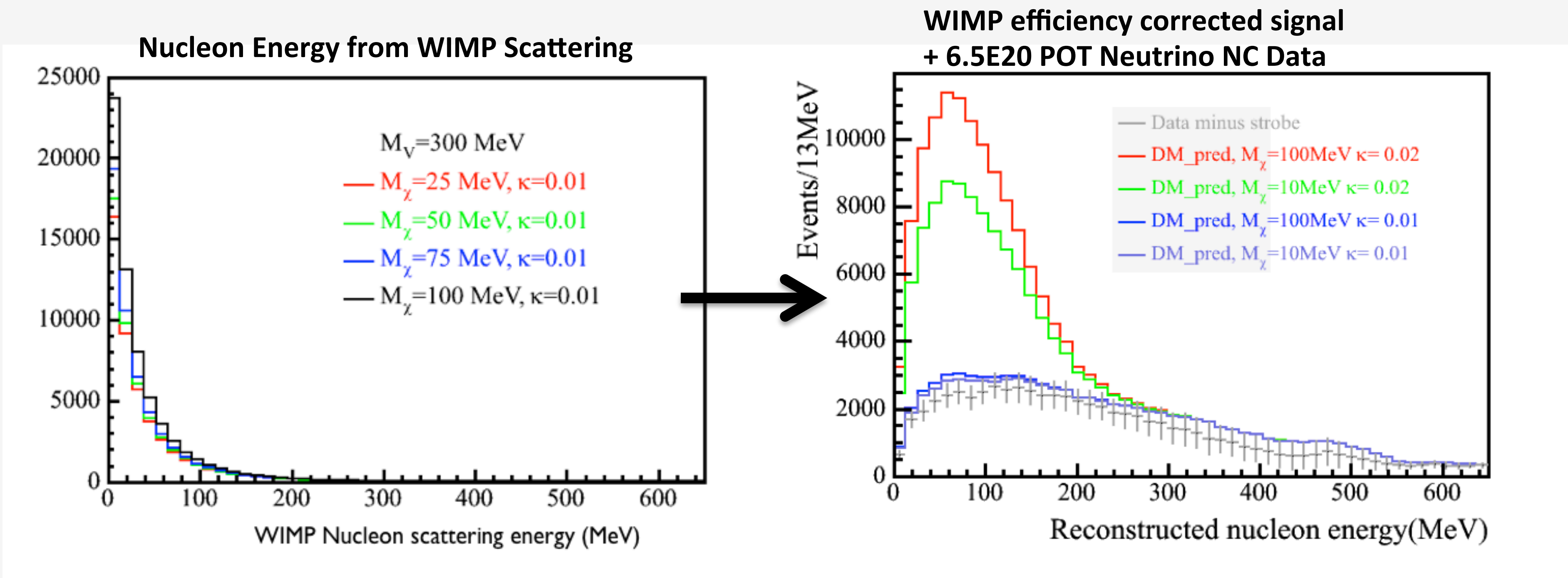
- Estimate 90% C.L. upper limits includes $\cos\theta_{beam}$ and timing info.
- Can cover a significant part of the muon g-2 signal region.

The MiniBooNE 2012 PAC Request

MiniBooNE requests running to collect a total of [illegible].0 × 10^{20} POT in beam off target mode and with the 25m absorber deployed. This will allow a powerful search for light mass WIMPs in a parameter space that overlaps with muon $g - 2$ and cosmic relic density estimates. The experiment further requests that this beam be delivered in FY2013 and 2014 before the MicroBooNE experiment turns on.

- Search for low mass WIMP signals is compelling and explores uncharted territory.
- In the period before MicroBooNE turns on (~1 year) we put the idle Booster Neutrino Beamline (BNB) to good use that will produce publishable physics.
- Proposal rejected, physics was motivating but cited a lack of remaining collaboration strength, and not completing the WIMP scattering analysis on the current data sets.

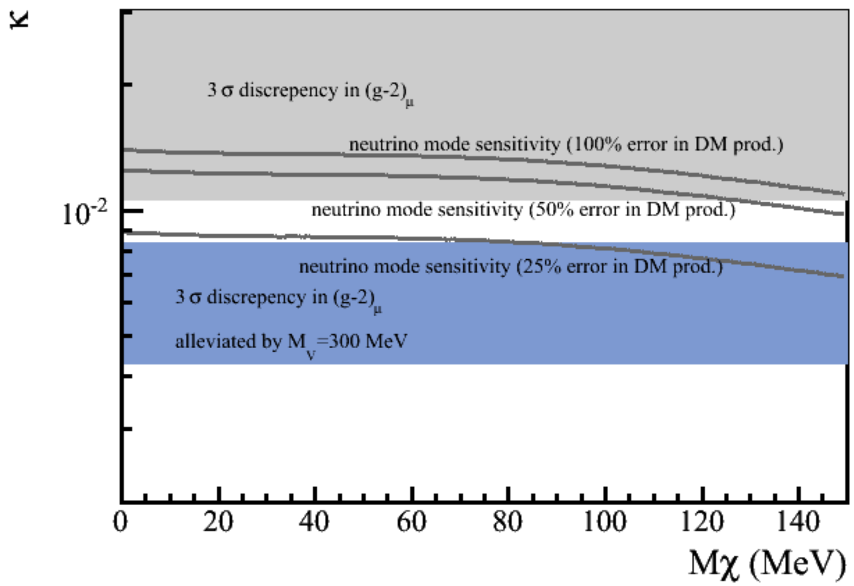
Work Since the PAC Decision: Using Energy to Fit to the Neutrino NC Data



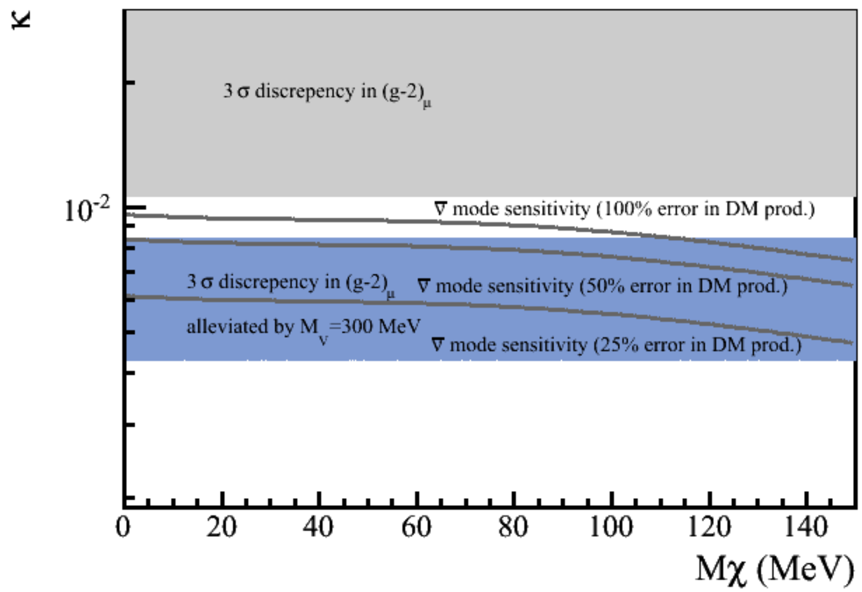
- Fit the WIMP template plus the neutrino background prediction to the NC data.
- Most of the WIMP signal resides $E_{nucleon} < 200$ MeV.
- Fits done by MiniBooNE's Ranjan Dharmapalan (U. Alabama).

Sensitivity derived from WIMP Nucleon Scattering Fits to the 6.5E20POT Neutrino and 10.1E20POT Antineutrino (Monte Carlo)

Neutrino 6.5E20 POT

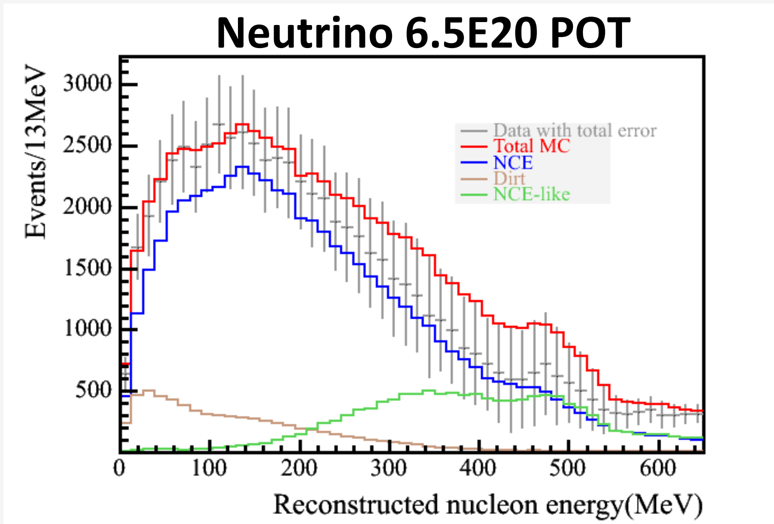


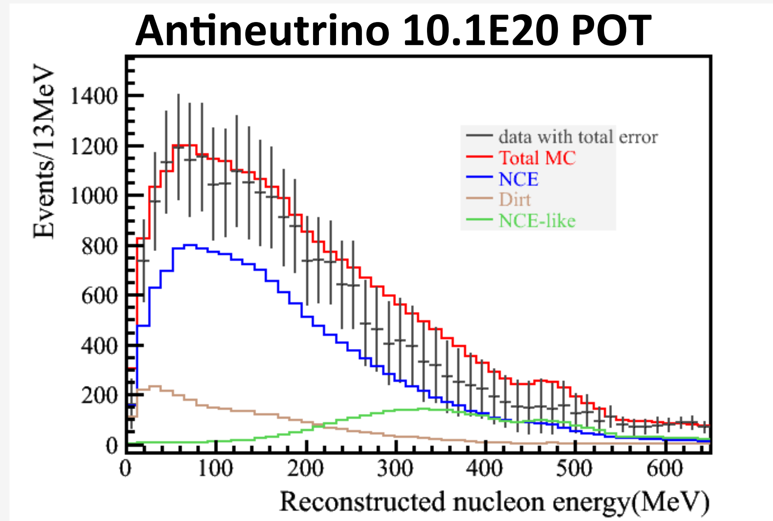
Antineutrino 10.1E20 POT

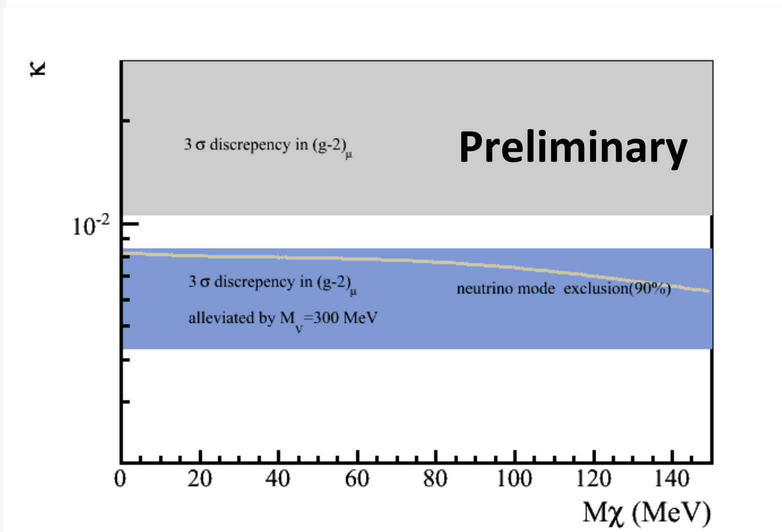


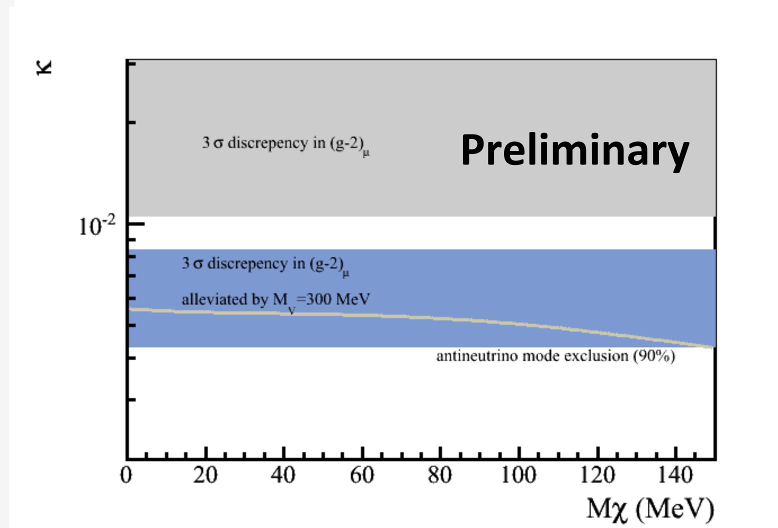
- Limits better than anticipated due to the use of energy. However, still does not completely cover the interesting g-2 signal region.
- WIMP production errors can have a noticeable effect.
- Antinu better due to x2 stats and four times less backgrounds.
- Timing analysis is almost complete and will be applied soon!
- WIMP-electron scattering will give best sensitivity, but more work needed to push down energy thresholds below 140 MeV.

Limits derived from WIMP Nucleon Scattering Fits to the 6.5E20POT Neutrino and 10.1E20POT Antineutrino Data



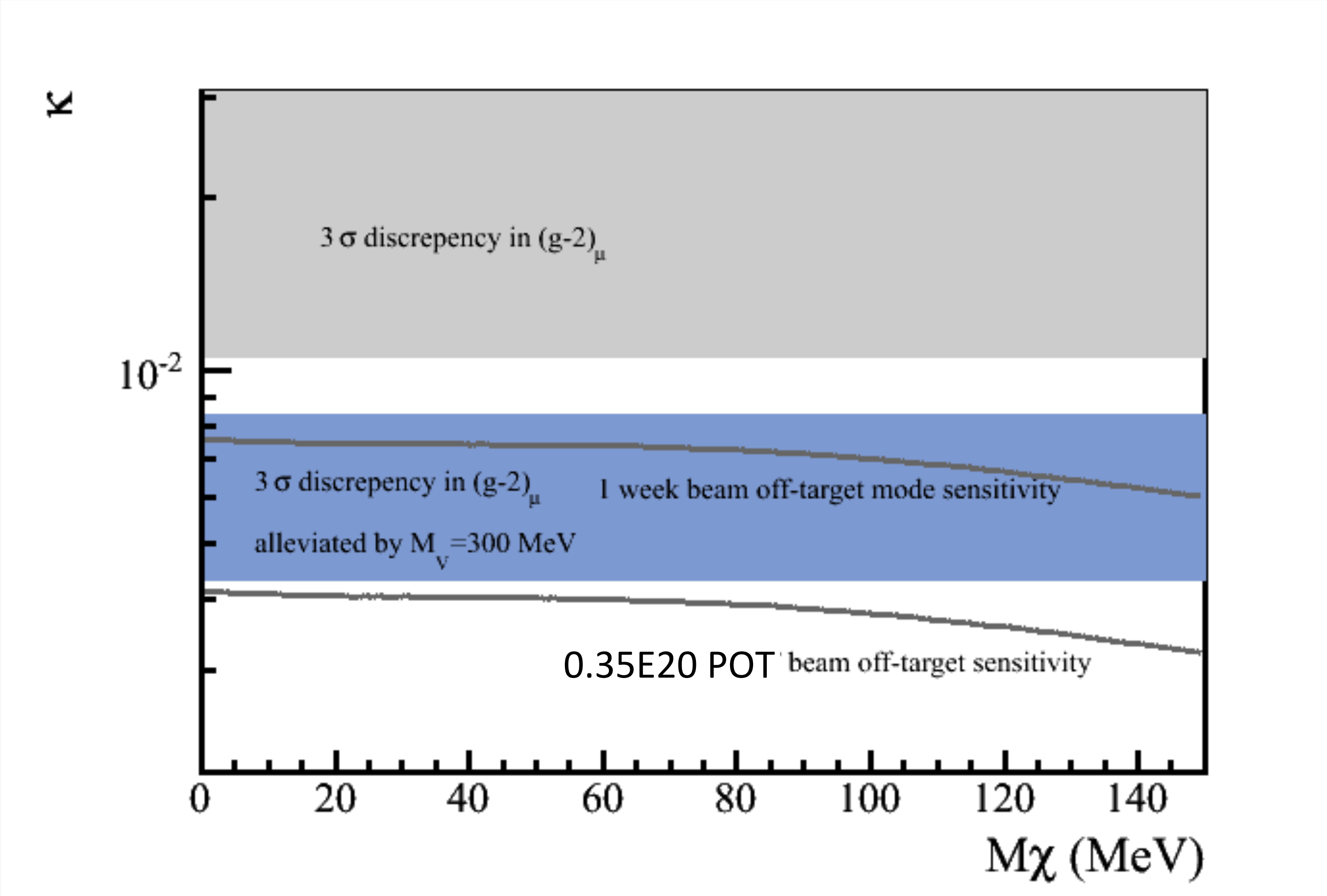






- Limits assuming 25% production error.

What can we do with 0.35E20POT Beam off Target Running and the 50m Dump



- Can cover most of the g-2 signal region with only 0.35E20POT!
- Larger production errors will hurt, but timing will help.

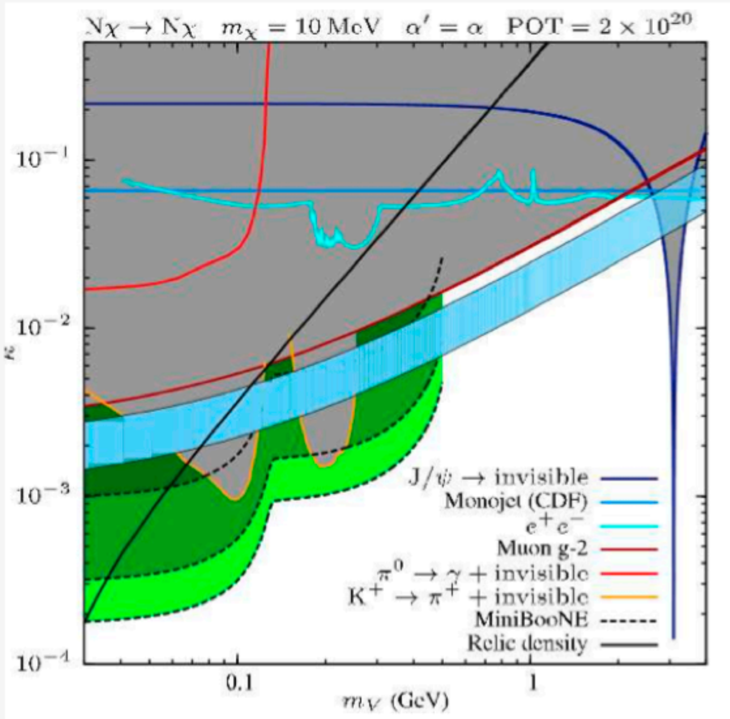
A new opportunity presents itself: FNAL Beamline Commissioning

- Summer of 2013, FNAL is coming out of a long shutdown after major upgrades to the Booster and Main Injector which require months of commissioning, e.g. putting the protons on a beam dump.
  – What better beam dump than the BNB!!
- Recent analysis has demonstrated we need ~0.35E20 POT, which is only 2-3 months of running! Recent discussions with FNAL management encouraging…
- A statement of support from the IF5 community could help secure the run!
- Recalls Thursdays talk by **Yuval GROSSMAN**:

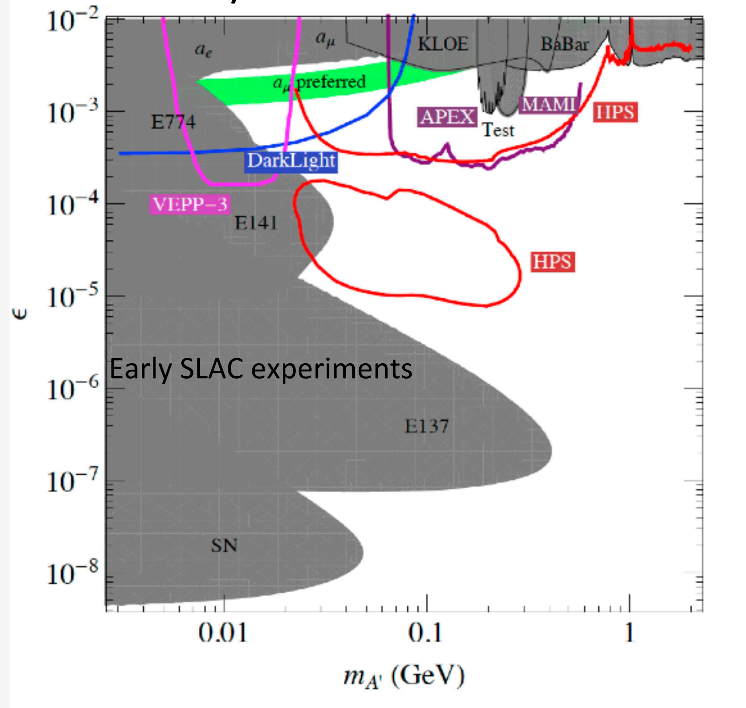
$$R_{NPC} \equiv \frac{\text{Prob to find NP}}{\text{Cost}}$$

I don't know Prob, but cost is small. We should do this!!

Two Regimes for Light Mass WIMP Models: We Need to Investigate both Regimes!



$\varepsilon = \alpha'/\alpha$



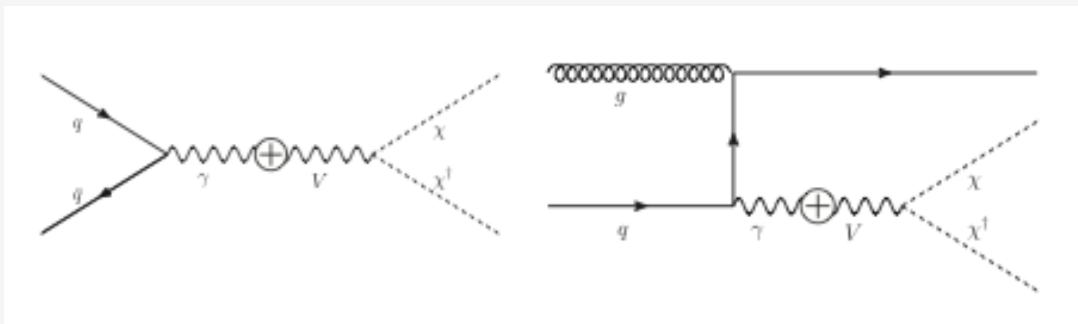
$M_v > 2M_{wimp}$
Br(V -> SM) ~ $\kappa^2\alpha'/\alpha$
"Invisible V decay"

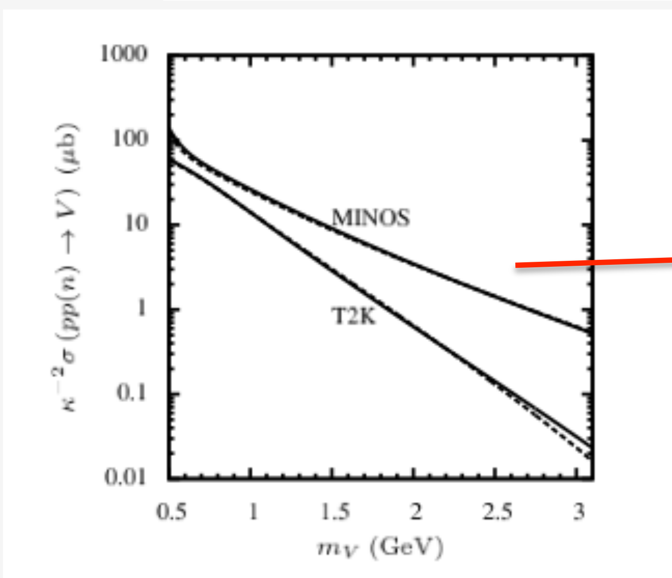
$M_v < 2M_{wimp}$
Br(V -> SM) ~ O(1)
"Visible V decay"

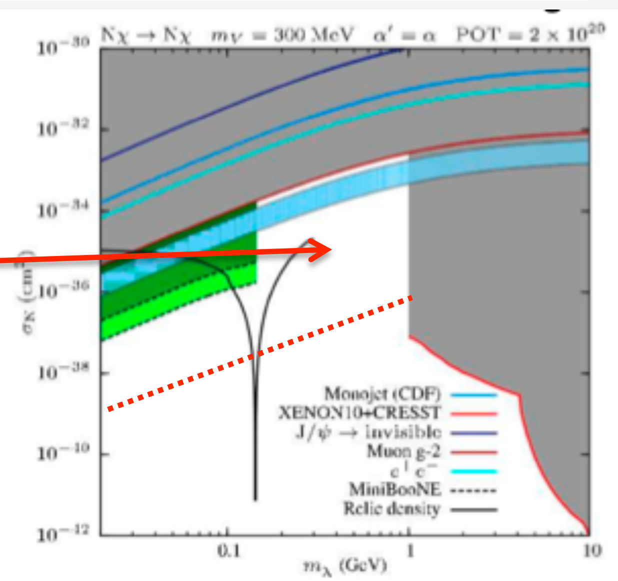
- Electron and Proton dump experiments compliment each other and extend the search for the hidden/dark sector!
- LSND V->e+e- limits on the right plot, M_v < 100 MeV, and $10^{-4} < \varepsilon < 10^{-6}$

Extending the WIMP search using the Main Injector

- With the higher energy protons (120 GeV), the direct production channel dominates.







- With MI experiment we can fill in the M_x gap up to the direct detection experiments, and go lower in cross section!

Developing Experiment for Main Injector and Project X

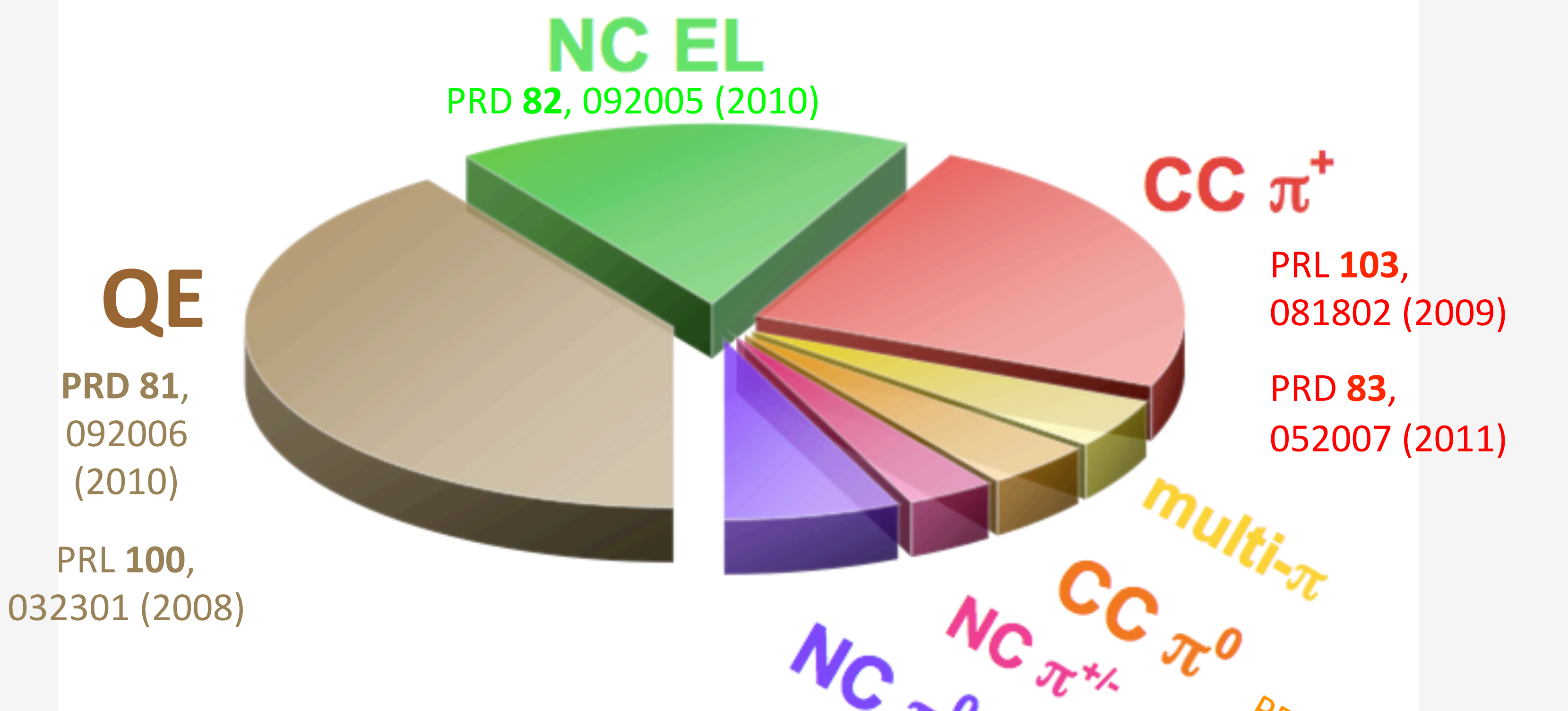
- Design a dedicated beam dump (NuMI cannot run in beam off target mode).
  - With better design, suppress the neutrino flux by >> 1000!
  - Pay attention to improved beam timing.
- Develop a high spatial/timing resolution detector. Require >100 tons.
  - Scintillator fiber detector: 3mm spacing, with ~250 picosecond timing. ~1 MeV threshold. Expensive!
  - Large Area Picosecond Photo-Detectors (LAPPD). Work in progress.
- **MI dump experiment takes advantage of future development of Project X, which will deliver many more protons to the Main Injector.**

Conclusions

- A 2-3 month MiniBooNE beam off target run will result in relevant and interesting light WIMP limits (or possible signals??).
  - Explores new regions of WIMP parameter space that are consistent with relic density estimates and g-2 anomaly.
- The MiniBooNE beam off target run can help motivate future beam dump experiments and Project X
  - Calculating sensitivities for MicroBooNE (LAr ~8 times less fiducial mass), might propose a beam off target run after 3yr neutrino run.
  - MI 120GeV proton dump experiment will have significantly better reach in WIMP mass and cross section.
  - **Project X is a natural machine to search for the hidden/dark sector, this needs to be highlighted as a justification for the machine.**

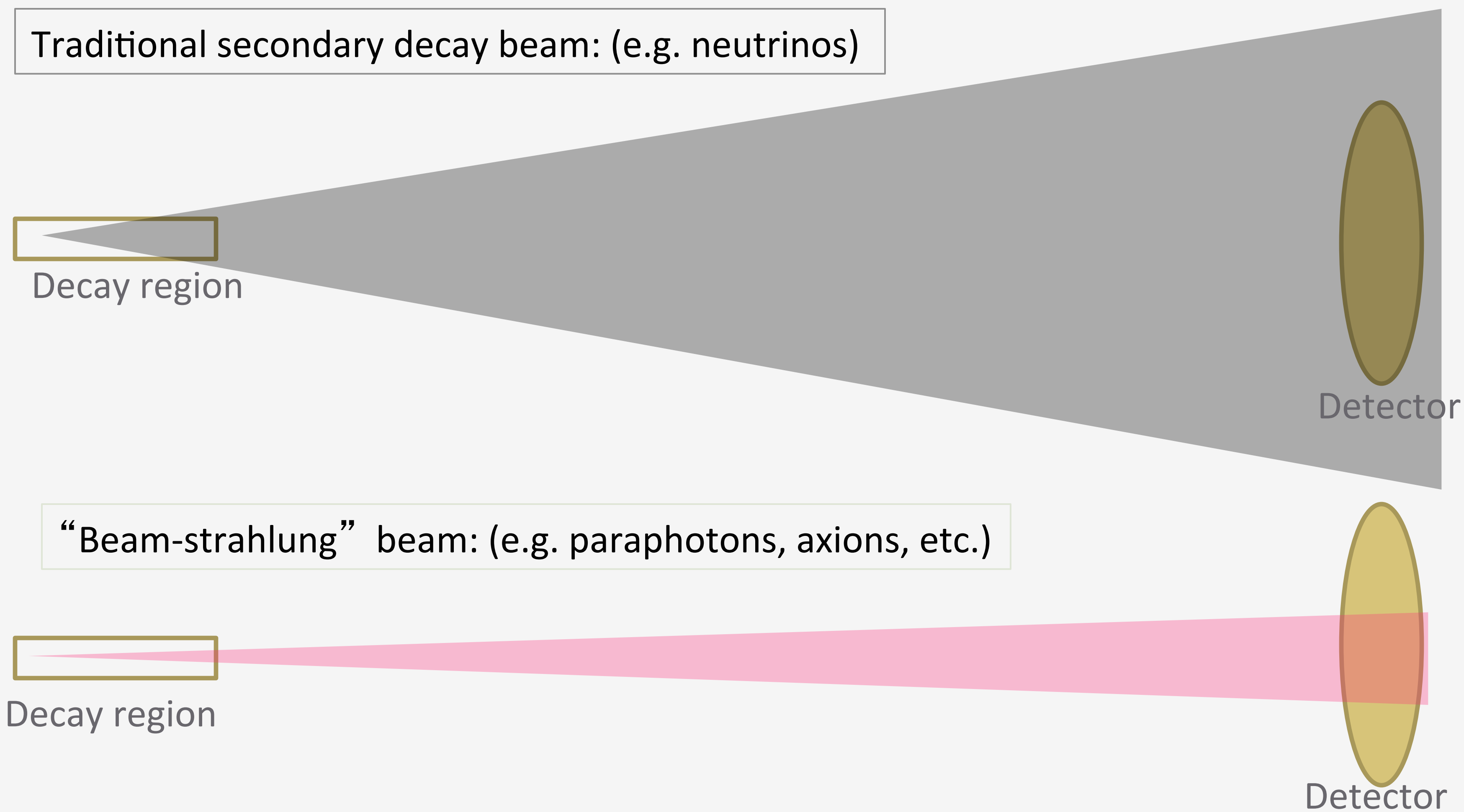
BackUp Slides

Ten Years of MiniBooNE Running: Cross Section Results



- We have measured cross section for **90%** of ν interactions in MB. The detector is well understood!
- $\overline{\nu}$ results on CCQE and NC will be published soon.
- These results have motivate much new and needed theoretical work on neutrino nucleus scattering (> 540 citations)

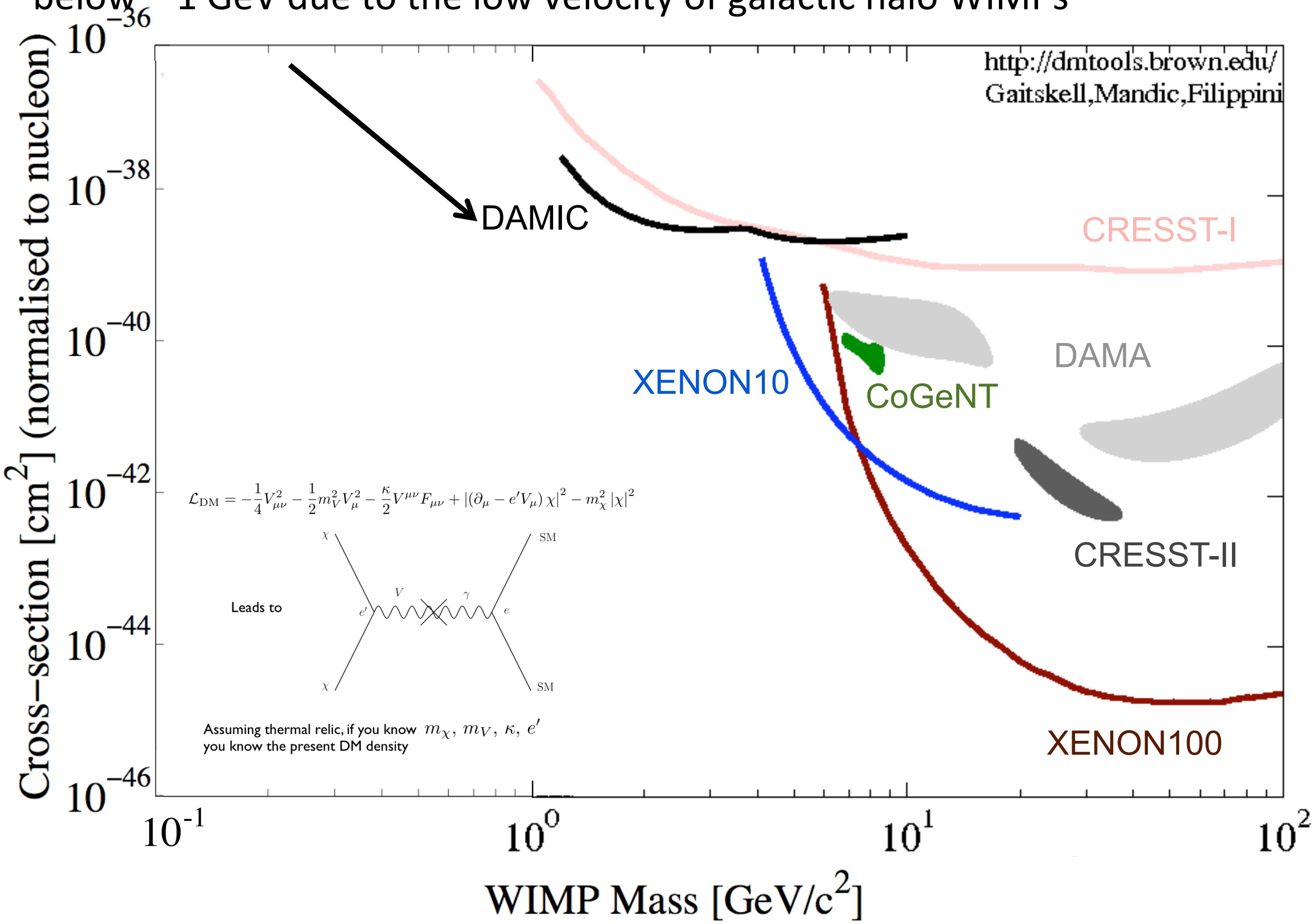
Beam-strahlung



The "brem-ed" particles will be tightly collimated around the incoming proton beam direction (<~0.5 mrad) and will either decay or scatter in the center of the detector (assuming on-axis beam!)

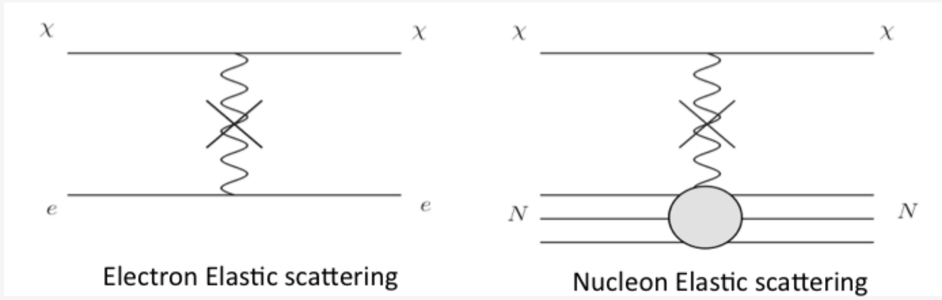
World Data on Low Mass Spin Independent WIMP Scattering

Traditional underground direct detection experiments run out of sensitivity below ~1 GeV due to the low velocity of galactic halo WIMPs



However, for low mass WIMPs (< 1 GeV) you need a new model to produce the right relic density!

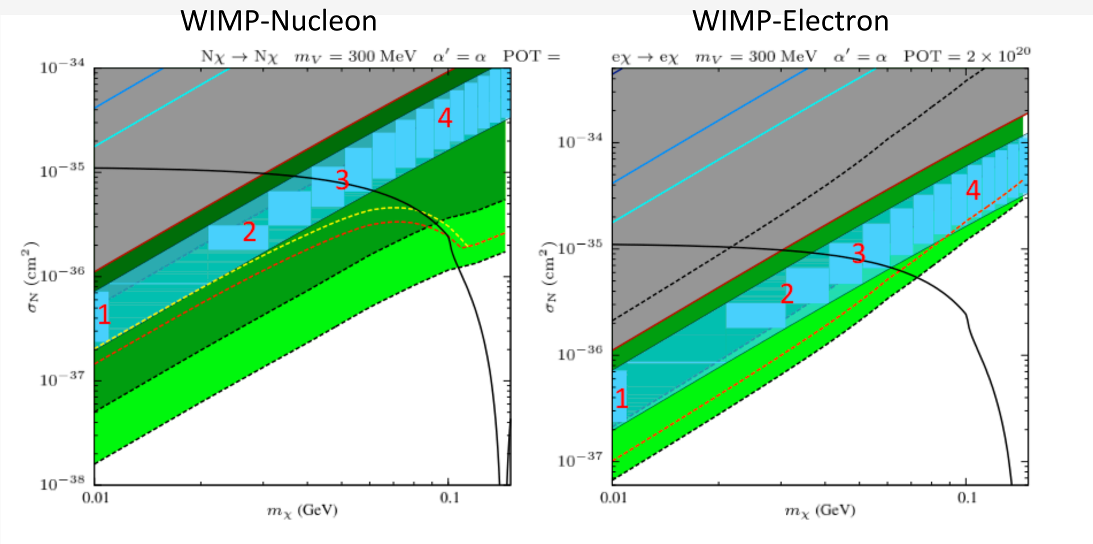
Estimating MiniBooNE WIMP Detection Sensitivities



- Nucleon xsection larger due to center of mass energy scaling $\sigma \sim E_{CM}$.

- WIMPs (χ) can interact in the oil scattering off nucleons and electrons.
  - WIMP events look like neutrino NC scattering off nucleons or electrons but possibly with different kinematics (momentum, angle, timing, etc).
- Can use different techniques to extract signal (there might be more)
  - Neutrino flux reduction (beam off target running)
  - Counting
  - Energy and/or angle fit
  - Timing fit
- Can also use combinations of the above four methods to increase signal over background

Estimated WIMP Signal Significance:
2E20 POT Beam off Target and **25m** Absorber Run



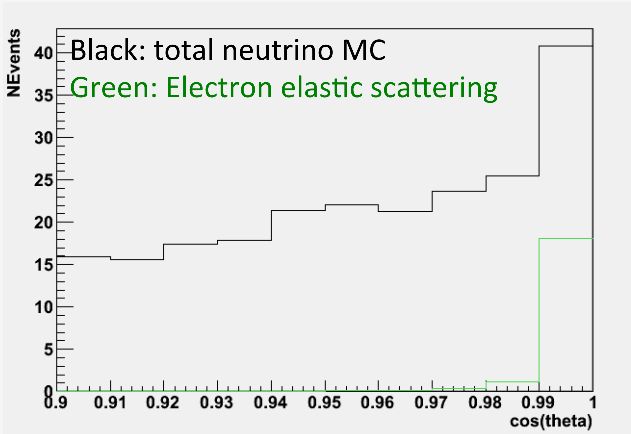
- Signal, backgrounds and significance for various M_x and σ points in the g-2 band.
- g-2 band mostly covered at > 5σ

Pt.	Scattering Channel	Beam Mode (2.0×10^{20} POT)	WIMP mass (MeV)/ cross section (cm^2)	Signal	Background and Errors	Probability
1	Nucleon	25m	$10/4 \times 10^{-37}$	1859	350±66	$< 10^{-10}$
2	Nucleon	25m	$30/3 \times 10^{-36}$	1453	350±66	$< 10^{-10}$
3	Nucleon	25m	$50/8 \times 10^{-36}$	1326	203±40	$< 10^{-10}$
4	Nucleon	25m	$100/3 \times 10^{-35}$	1186	9.2±3.4	$< 10^{-10}$
1	Electron	25m	$10/4 \times 10^{-37}$	13.2	0.15	$< 10^{-10}$
2	Electron	25m	$30/3 \times 10^{-36}$	7.7	0.15	$\sim 10^{-9}$
3	Electron	25m	$50/8 \times 10^{-36}$	4.8	0.09	$\sim 10^{-6}$
4	Electron	25m	$100/3 \times 10^{-35}$	1.4	0.004	$\sim 10^{-3}$

Pt. 3 is overlap of g-2 and relic density

Fits to our Electron Sample will be much more sensitive

- $\cos\theta_{beam}$ cut reduces backgrounds by x100



- Will cover entire g-2 region up to ~200 MeV.
- However, current energy threshold > 140 MeV, this needs to be reduced to > 50 MeV to improve sensitivity. Working on it!